Design of Adaptive Autoreclosure Schemes for 132 kV Network With High Penetration of Wind—Part I: Real-Time Modeling

Simon P. Le Blond, *Member, IEEE*, and Raj K. Aggarwal, *Senior Member, IEEE*

***Abstract*—This paper is the first of a series of publications detailing the development of an AI-based adaptive autoreclosing (AA) algorithm. In part 1, a detailed model of the Scottish 132 kV network has been constructed on a real-time digital simulator. The system model is discussed, including the network topology, line and source modeling, and the doubly fed induction generator-based wind farm model. An initial investigation on the penetration of harmonics from local wind farms is conducted using short circuit faults on two transmission lines in the network. This is necessary to ascertain to what extent wind farms may interfere with the AA scheme. Along with validating the model, the results suggest that penetration of harmonics is only significant on lines adjacent to the wind farms.**

***Index Terms*—Power system protection, power system simulation, power system transients, power transmission lines, real-time systems, reclosing devices.**

NOMENCLATURE

TBP	Transient-based protection.
OHL	Overhead transmission line.
SPG	Single-phase-to-ground fault.
VSC	Voltage-source converter.
PWM	Pulsewidth modulation.
AI	Artificial intelligence.
AA	Adaptive autoreclose.
DFIG	Doubly fed induction generator.
Z'	Sub-transient impedance
$P_{\mathrm{s.c.c.}}$	Short-circuit power.
V_{l-l}	Line-to-line voltage.
I_{peak}	Bus peak current.
G	Stationary arc conductance.
τ	Arc time constant.
g	Time-dependent arc conductance.

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The authors are with the Department of Electronic and Electrical Engineering, the University of Bath, Centre for Sustainable Power Distribution, Bath BA2 7AY, U.K. (e-mail: s.p.le.blond@bath.ac.uk).

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I. INTRODUCTION

POWER SYSTEM protection and control is an area to which the smart grid revolution brings opportunities and challenges in equal measure. In the UK, in particular, an integral part of the short to midterm strategy for implementing a low carbon generation mix is a significant increase in wind generation. Latest government targets are 30% renewables in the generation mix by 2020 [1]. Recent advances in generation and power conversion have increased the scalability of wind power. Consequently wind farms will form some of the primary generators, along with many more embedded units connected at distribution level. From a technical perspective, the consequences of this for the UK system are two fold. The network operator must carefully consider the effect of high penetration of intermittent wind on maintaining the system, particularly angle stability, frequency stability, voltage control and power quality. Larger farms may also have an impact on the correct operation of protection and control equipment. Increasing demand and the greater distance between generation and major load centres, will lead to a concomitant decrease in transient stability margins as greater power is pushed through the networks. From a protection standpoint, this demands a shorter critical clearing time, the time in which circuit breakers must operate in order to maintain system stability.

In recent years, the academic community has extensively investigated transient-based protection (TBP) [2]. TBP uses the high frequency information, above the power frequency, within the transient fault signature to effect a relay decision. The advantages of such techniques are faster fault clearance times, immunity to electromechanical oscillations, power swings and subsynchronous resonance associated with reactive power compensation equipment. Since more information is contained in the wideband signal, transient-based relays are less vulnerable to maloperation caused by power system phenomena occurring at any localized frequency. In future, these techniques may be deployed in parallel with conventional power frequency-based relays to increase selectivity, security and dependability.

Despite potential advantages, the uptake of TBP among manufacturers is slow. Power systems are safety critical so utilities are naturally reluctant to install novel relays over proven techniques and, thus, manufacturers have less incentive to develop and support them. Moreover, a significant technical barrier is the need to consider the unique transient response of each item of primary equipment.

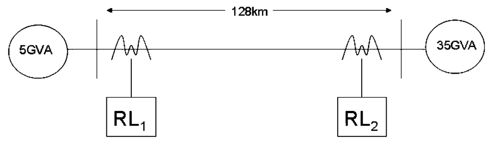

Fig. 1. Typical power system for investigating transient-based OHL relays.

Typically, novel unit-protection, including TBP, is developed using a much simplified power system model, with the component under study in between two busses, terminated in sources behind a subtransient impedance (see Fig. 1). However, when developing TBP, it is also important to model equipment outside the protected zone in order to be confident that it has no adverse effect on its performance.

Broadly speaking, the intended use of the test network described here is to develop a more realistic testing ground for TBP. The real world system will be used to evaluate the feasibility of TBP, and the effect of various power system components on TBP, including variable speed wind turbines.

This series of papers is concerned with the development of adaptive autoreclosing (AA) techniques. This is where the transient signature is used to diagnose the extinguishing of the secondary arc and, thus, the safe reclose times for temporary faults. Furthermore, reclosing is blocked for permanent faults minimizing secondary shocks due to failed reclose attempts and leading to increased equipment lifetime. Since the signature associated with a dynamic arc resistance manifests itself at high frequencies this technique must be based on transients. The method developed will be building on those presented in [3]. This model will therefore initially be used to develop and demonstrate a transient-based AA relay in real time.

II. Real-Time Digital Simulation

The real-time digital simulator (RTDS) is a proprietary product of RTDS Technologies. It uses parallel processing techniques on rack-mounted processors to maintain continuous real-time digital simulation of a power system of arbitrary complexity. The computation techniques are based on those developed by H. W. Dommel and used in the well-known Electromagnetic Transients Program (EMTP) software [3]. The advantage of real-time operation means that the power system operates in its own closed loop. The user may interact with the simulation in real time observing the effect of control actions.

The power system is drafted offline in a computer-aided design (CAD)-based program "RSCAD" and then uploaded to the RTDS hardware in real time via RSCAD's runtime module. Here, fault condition(s) can be applied and the long-term power system response can be analyzed and observed. If necessary, the user can interact with the simulation in real time via various control actions. These features combine to make a highly realistic simulation of a power system. The simulation time step is typically between 50–60 μs, meaning that for real-time operation, the RTDS must be capable of solving system conditions in under that time *for every successive time step*. RTDS Technologies state frequencies of up to 3 kHz can be reproduced with confidence [4].

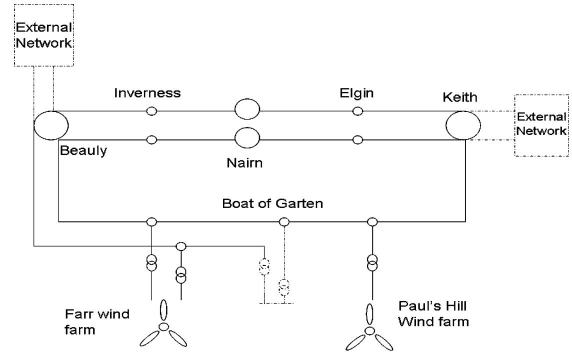

Fig. 2. Section of Scottish system under study; dashed components are omitted from the simulation.

III. Network Model—132 kV Primary System

The modelled network forms part of the 132 kV network in the Scottish Highlands. Currently, this network is owned and maintained by SHETL, part of the Scottish and Southern group, and operated by National Grid, the UK system operator.

The network comprises of eight 132 kV busbars in a ring topology as shown in Fig. 2. The northern branch of the network runs 90 km from Beauly to Keith, supplying the load centres of Inverness, Nairn and Elgin. To the south, a 50 km branch supplies a load at Boat of Garten collecting power on route from the Farr wind farm. Another 50 km branch runs from Boat of Garten to Keith via Paul's Hill wind farm, covering an area of approximately 1300 km^2. Although in the U.K., 132 kV is considered subtransmission, here the network forms the transmission system since there is no higher local voltage network installed.

The area is ideally suited for the study since it includes two wind farms, provides an area large enough for extensive real world studies, yet small enough to implement a real-time transient model with the processing power available. In addition, an important constraint on traveling wave models is that the travel time must be longer than the simulation time step. In this network all the lines are longer than 15 km, (a distance limitation imposed by RTDS's 50 μs time step) so they may be represented using traveling wave models. Since the entire network is at 132 kV, extensive transformer modeling is not necessary, freeing up valuable processing power.

A. Source Modeling

The grid infeed points at Beauly and Keith are represented using the RTDS source model behind an equivalent subtransient impedance. These are based on the short circuit values for the three-phase peak current at each busbar, taken from National Grid's seven year statement [5]. The subtransient impedance is calculated by

$$P_{\text{s.c.c.}} = V_{l-l}\left(\frac{\sqrt{3}}{\sqrt{2}}I_{\text{peak}}\right) \tag{1}$$

$$Z' = \frac{V_{l-l}}{P_{\text{s.c.c.}}}. \tag{2}$$

The X/R ratio is then taken to be 13.5, an average of the values for 132 kV quoted in [6]. This then gives the positive sequence impedance and phase angle that may be entered directly into RSCAD's source component. Strictly speaking, the sources should be represented by a dynamic impedance, where the subtransient reactance becomes the transient value and steady state reactance about 0.5 and 2 s post-disturbance, respectively. This is beyond the scope of the paper due to limited information and computational power. However, since the phenomenon under consideration is mostly in the fast transient range, under 0.5 s, this approximation is reasonable.

B. Line Modeling

The 132 kV overhead lines in this part of the network are predominantly of the double circuit tower type, typical of the U.K. system. The exception is the line connecting Keith to Boat of Garten, which is a single circuit. The conductor is the *Lynx* type with a single conductor per phase on all lines. The lines are not long enough to require transposition so the RTDS model was set to reflect this. All of the line configurations can be found in Appendix A.

The RSCAD-line modeling program allows RLC-type data entry. The information associated with each circuit is public domain and can be found in [5]. However, for the greatest accuracy and transient frequency response, RSCAD requires physical data associated with the lines, including conductor configuration. The line data for the network can be found in Appendix B, and are reproduced with permission of Scottish and Southern Energy.

The RTDS line models are distributed-parameter and frequency dependent, based on traveling wave theory. The line parameters are represented using hyperbolic functions in the frequency domain and then transferred to the time domain using convolution and the inverse Fourier transform. For simplicity, the assumption is made that the transformation matrix is frequency independent when this is not the case in reality. This does introduce some degree of error at dc and low frequencies, as the transformation frequency is generally chosen to be higher than the power frequency. However, the study is not concerned with subsynchronous frequencies at this stage so this limitation should not be too onerous. For the double circuit lines a six conductor model is used which is able to determine intercircuit coupling as well as inter phase coupling. A detailed discussion of traveling wave theory and its application for RTDS models can be found in [4].

C. Loads and Power Flow

Loads are assumed to be purely inductive, and are modelled using a passive shunt inductance and a resistance connected at the relevant busbar. The real and reactive loads were aggregated, based on the data in National Grid's estimated peak power flow for winter 2009 [5]. The true dynamic nature of loads was neglected since they are not critical, either at this voltage level or over the short timescales under investigation.

In RSCAD, initial conditions must be specified for the network sources and the generators within the network. These then settle down to a steady state after the simulation begins real-time operation. Initial conditions were based on the peak power flow for winter 2009 published in National Grid's seven-year statement [5].

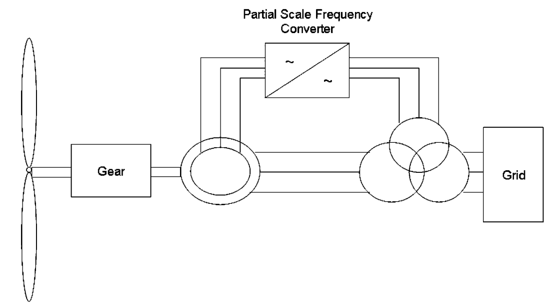

Fig. 3. Basic diagram of the DFIG turbine.

D. Wind Farm Model

The Farr wind farm is located approximately 16 km south of Inverness. It consists of 40 Bonus/Siemens 2.3 MW wind turbines, to give a total installed capacity of 92 MW. Paul's Hill wind farm lies 23 km southwest of Elgin and with 28 $\times$ 2.3 MW turbines of the same manufacturer and model. The generators in the turbines are of the modern variable-speed DFIG type. The DFIG (doubly fed induction generator) is an induction generator where partial power conversion is handled by back-to-back converter.

The induction generator's rotor is connected to a partial frequency converter via slip rings, which in turn is coupled to the grid through a three-winding transformer. The stator of the generator is connected directly to the grid as shown in Fig. 3. The power electronic converter makes up for the shortfall or excess speed difference (and, thus, the difference in the turbine's mechanical frequency and the grid's electrical frequency) by injecting the appropriate variable current into the rotor. In the oversynchronous case, power flows from the rotor to the converter to the grid, and in the subsynchronous case it flows in the opposite direction. However, in either case, net power flow is onto the grid via the stator. This mechanism enables the turbine to operate at a wide range of speeds, typically up to $+30\%$ and -40% of synchronous speed.

The back-to-back converter enables two-way power flow, consisting of a rectifier and an inverter whose thyristors are pulsewidth modulated. Fast discrete switching of the thyristors, controlled by modulating the width of signal pulse approximates a dc input signal to a sinusoid and vice versa. The basic premise is that power is taken at one ac frequency, converted to dc and then converted back to ac at the required grid frequency. The capacitor across the dc link allows control of the rectifier and inverter to be decoupled. This means more complex control of the thyristors can be introduced to suit the requirements both at the grid side (i.e., reduce power fluctuations and control voltage) and at the generator side (appropriate excitation currents can be established along with the desired rotor speed). It is the fast switching of the semiconductor thyristors that introduces harmonics onto the grid [7].

Unfortunately, transient models of the particular turbine design are not available since they are proprietary to the manufacturer. However, a generic model of a DFIG wind turbine has been developed by RTDS Technologies. A more in-depth explanation of the model can be found in [8]. Briefly, the wind farm includes a mechanical model of the turbine, whose input wind speed, pitch and, thus, mechanical torque can be adjusted in real time. The switching of the thyristors for both the grid side and the rotor side is decoupled and governed by two separate vector control schemes. This means that on the grid side, frequency can be maintained and real and reactive power can be independently controlled. On the rotor side, maximum energy capture over a wide range of wind speeds is achieved. The model of the partial power converter uses the small time step (below 2 μs) VSC component of the RTDS. An interface transformer converts signals from the small time step module to the main power system time step. This is necessary for the fast switching resolution of the PWM voltage source converters. A discussion of how this is achieved in real time, and the interfacing with the main power system can be found in [4] and [9]. Ideally, the wind farm would be modelled using the full number of turbines but this would require considerable processing power. Therefore, a single turbine model has been scaled up to represent the installed capacity of the entire wind farm. It should be stressed that for the harmonic study in Section IV, the wind farms were represented by ideal harmonic sources. This model is only used to develop the AA scheme in part 2, as described in the further work section.

IV. Network Model—Secondary System and Miscellaneous

A. Transducer Modeling

An important aspect of designing transient-based protection schemes is including the transient response of the instrument transducers. The RTDS includes models for a capacitive voltage transformer (CVT) for measuring primary system voltages, and a current transformer (CT) for system currents. Modeling the transient response of transformers is necessary since some conditions may initiate ferroresonance and inrush phenomena that may confuse or compromise relay functionality. A detailed discussion and an investigation into the effect of these models is reported in [10].

B. Arc Modeling

In AA schemes, it is necessary to determine whether a fault is transient or permanent. Transient faults exhibit arcing behavior, with high frequency signatures due to a dynamic resistance. In the design of the scheme it is necessary to simulate the arc and its interaction with the power system, so that the logic may respond appropriately to an arcing fault or a permanent fault.

The arcing behavior can be described by the primary and secondary stages. The primary arc is in the period before the circuit breakers open and is due to the fault current flowing from the energized phase to ground. The lower current secondary arc is sustained by the mutual coupling between the faulted and healthy phases, and only present when one or more of the phases remain energized. The behavior of both arcs are governed by time varying conductance, and can be described by (3) the dynamic equation for unconstrained arcs in air

$$\frac{dg}{dt} = \frac{1}{\tau}(G - g) \tag{3}$$

TABLE I
G 5/4 Recommendations for the First 9 Harmonics on Systems Between 20 and 145 kV

Harmonic Number (h)	Harmonic Voltage %	Harmonic Number (h)	Harmonic Voltage %
2	1	6	0.5
3	2	7	2
4	0.8	8	0.4
5	2	9	1

where G is the stationary arc conductance, g is the time dependent arc conductance and τ is the time constant. The secondary arc is more complex because it has a varying arc length, on which the time constant depends, and a number of successive partial restrikes. Arcing signatures also may be significant as a result of the action of the circuit breakers. Since the RTDS circuit breaker model operates at a current zero crossing it is assumed that no arcing takes place. As discussed in the further work section, arc models and their implementation into the network model is discussed in detail in part two of this paper.

V. Harmonic Penetration Study

A suitable starting point for the study is to determine the extent to which harmonics generated by the wind farms penetrate onto the local grid. This is important for AA since harmonics may mimic high frequency information associated with the arcing fault, leading to a permanent fault being misdiagnosed as transient. A wind farm must comply to operating constraints imposed by the utility, known collectively as the *grid code*. An important aspect of this is ensuring a certain degree of power quality. The U.K. grid code demands all generators to be compliant to Engineering Recommendation G5/4 [11], which in turn is based on the international standard IEC61000. This governs the levels of harmonic distortion permissible, up to and including the 50th harmonic. ER G5/4 recommends the following planning levels for harmonic voltages in systems between 20 and 145 kV.

In practice, wind farms have filters to suppress the level of harmonic distortion and the operational levels should be well below the planned levels. However, as a worst case scenario, harmonic emissions should not exceed those stated in G5/4. The harmonic source component in RSCAD allows up to four harmonics superimposed on the fundamental ac sinusoidal source. The magnitudes of the harmonics are expressed as a percentage of the fundamental. In order to assess the worse case scenario, harmonic emissions equivalent to G5/4 levels were used to represent both wind farms. (The DFIG wind farm model discussed earlier will be used for subsequent investigations). It has been observed with PWM back to back converters, the 5th and 7th harmonics are most significant occurring at 250 Hz and 350 Hz, respectively [12]. The four harmonics were chosen to be the 3rd, 5th, 7th and 9th with respective harmonic voltage levels of 2%, 2%, 2% and 1%, per G5/4.

A. Simulation Setup

As mentioned before, of particular interest to the authors are transient-based AA schemes. During a single-phase-to-ground fault, the current and voltage waveforms were measured at the OHL terminating busbars in front of the breakers, since this is where the transducers will be based in practice.

Short circuit studies were conducted on the Beauly/Farr line, defined as "adjacent" and the Nairn/Elgin line defined as "distant." These lines were chosen since the former was adjacent to the wind generation, whereas the latter is the most distant. Also, the lines are of a similar length, both suitable for phase domain traveling wave models on the RTDS. For each line, an equivalent control case was conducted for comparison. In the control cases, the wind farms were represented by sources without harmonics.

For each case, a single-phase-to-ground fault was initiated at the midpoint of the line and the corresponding phase circuit breakers subsequently tripped at either end of the line simultaneously. The fault path resistance to ground was assumed to be 2 Ω. The AA schemes make use of frequency domain information. There is greater frequency domain information when single pole tripping is used over three phase tripping due to mutual inductive and capacitive coupling between the faulted and healthy phases. Although three-phase tripping is used extensively on the U.K. system, the circuit breakers were set to trip a single phase for the purposes of this investigation. (However, AA for three phase circuit breakers may be possible on U.K.-type double circuit lines by using the signature arising from intercircuit coupling.

B. Simulation Results

The time domain graphs all show a partial voltage collapse and large overcurrents caused by the single phase to ground fault. The circuit breaker responded between one and three cycles later and causes a total voltage and current collapse. Following the breaker operation the voltage attenuated over a short period as the isolated trapped charge is reflected up and down the line. The frequency spectra were obtained using MATLAB's inbuilt fast Fourier transform (FFT) routine, windowed over 10 power system cycles, two of which took place prefault.

It should be noted that the circuit breaker response varies from one to three cycles, due to the breaker logic requiring a coincidence of a voltage zero followed by a current zero. However, since the frequency domain information is of interest, the inconsistent response time of the circuit breaker does not significantly affect the results.

The study showed that there was significant penetration of harmonics onto the adjacent lines. This can be seen in Fig. 4, which shows the frequency spectrum for the healthy phase voltage for the sending end busbar. Fig. 4, which shows the 3rd, 5th, 7th, and 9th with the harmonics can be directly compared to the control case shown in Fig. 5 that did not have harmonic sources at Farr and Paul's Hill wind farms.

In the case of the adjacent line, there is significant generation nearby, and so the transients were suppressed due to the local strength of the grid. This can be seen in Figs. 6 and 7, which show the voltage time domain for the sending end with harmonics and the control case, respectively. The effect of mutual coupling in the healthy phases was particularly suppressed, as shown in Figs. 5–7.

In comparison, the distant line has significant mutual coupling between the healthy and faulted phases on the voltage

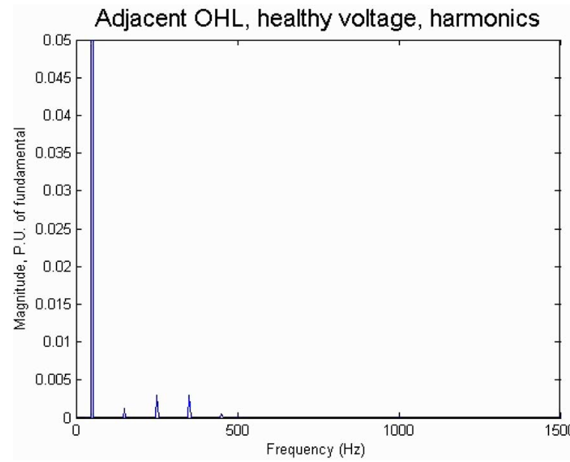

Fig. 4. Voltage frequency spectra, healthy phase, and adjacent line with harmonics.

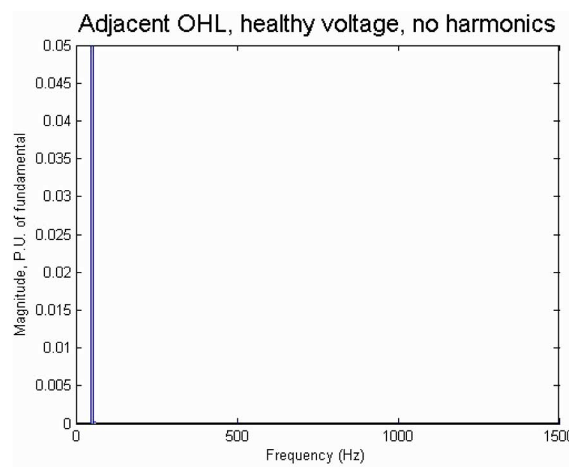

Fig. 5. Voltage frequency spectra, healthy phase, and adjacent line without harmonics.

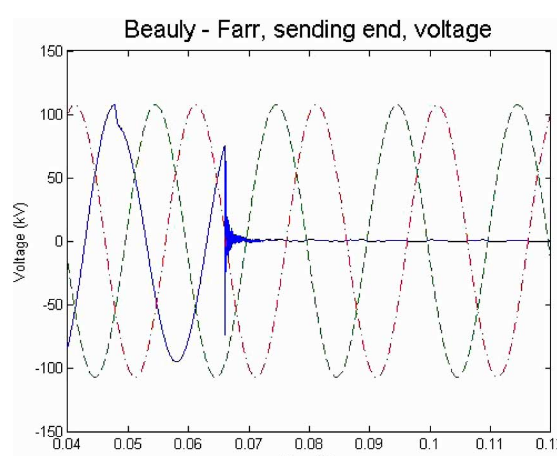

Fig. 6. Time domain voltage, all phases, adjacent line with harmonics.

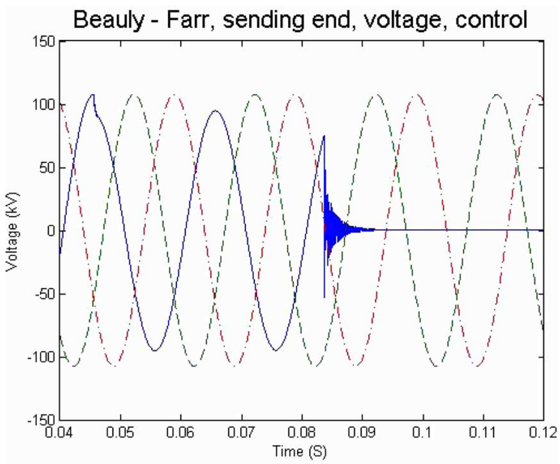

Fig. 7. Time domain of voltage, all phases, adjacent line without harmonics.

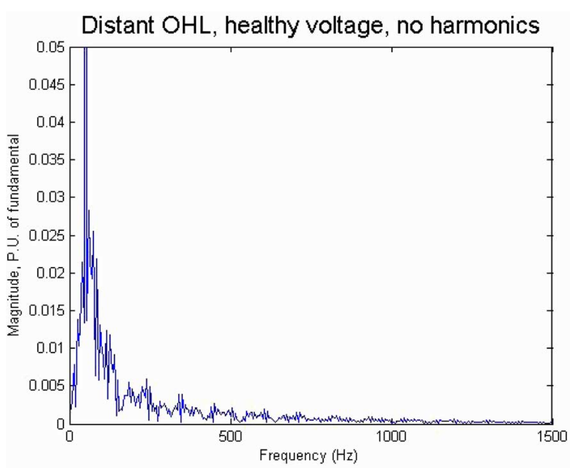

Fig. 8. Voltage frequency spectra, healthy phase, distant line without harmonics.

waveforms. This can be observed in Fig. 8, which shows the frequency spectrum for one of the healthy phases *without* harmonic sources.

Due to this pronounced mutual coupling, it cannot be determined to what extent the harmonics penetrate onto the voltage signals at this location on the grid. This is so because the coupling swamps the frequency spectrum on the distant line. The magnitude of the coupling here is even greater than the harmonics on the adjacent line. A comparison can be made between Figs. 4 and 8. In other words, if coupling to this extent was present on the adjacent line, the harmonics would not be clearly observed even though this line is electrically closer to the wind farms.

However, the current signals and corresponding spectra of the distant line (Figs. 9 and 10) suggest that wind farm harmonics do not significantly penetrate this far. This can be concluded when these plots are compared to healthy phase current frequency spectra on the adjacent line with harmonics, shown in Fig. 11. Incidentally, since the absolute current on the healthy phases was much smaller in comparison, there is a very significant harmonic component in proportion to the fundamental. The reduced current is due to much less real power transfer on both circuits between Farr and Beauly than on those between Elgin and Nairn.

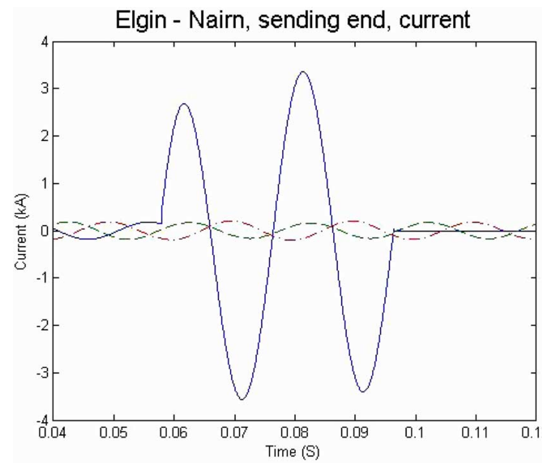

Fig. 9. Time domain of currents, all phases, and distant line without harmonics.

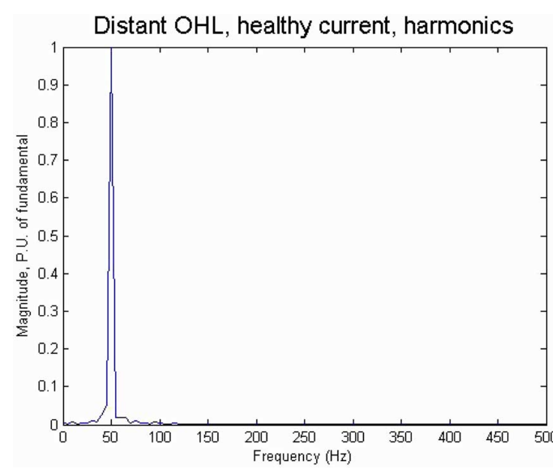

Fig. 10. Current frequency spectra, healthy phase, and distant line with harmonics.

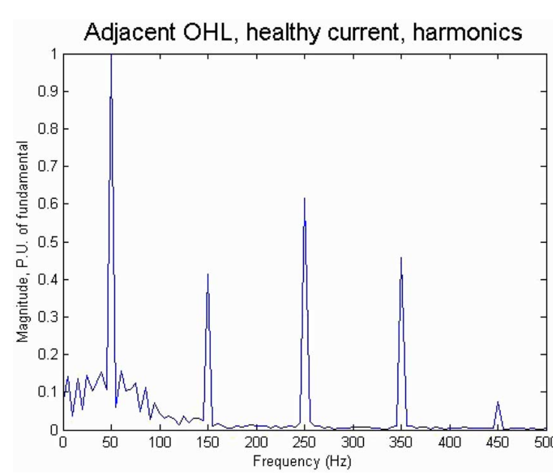

Fig. 11. Current frequency spectra, healthy phase, and adjacent line with harmonics.

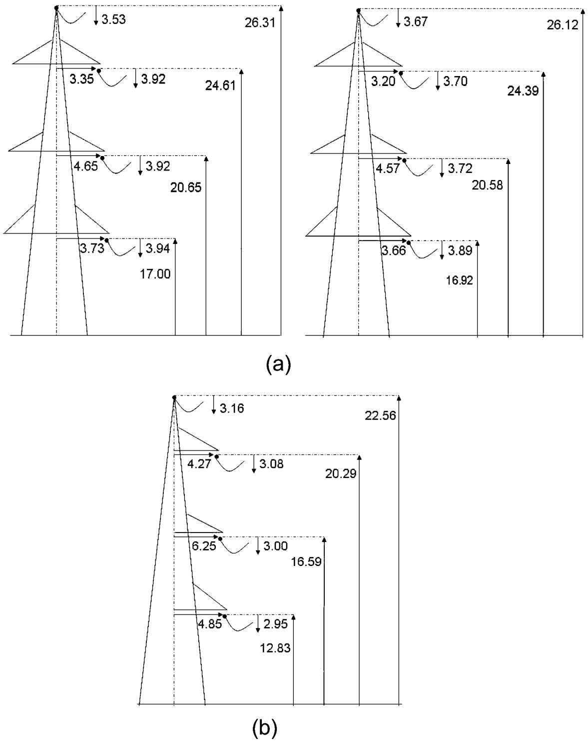

Fig. 12. (a) Double circuit towers, from left to right: Beauly to Boat of Garten OHL and Beauly to Keith via Nairn OHL, geometric configuration, showing horizontal and vertical placement, conductor positioning and conductor sag at midspan. (b) Single circuit tower, Boat of Garten to Keith OHL geometric configuration, showing horizontal and vertical placement, conductor positioning and conductor sag at midspan.

C. Discussion

Typical AA schemes rely on diagnosing the extinguishing of the secondary arc using a combination of signal processing and AI, such as neural networks or fuzzy logic [3]. The time series information is transferred into the frequency domain, and different bandwidths form the inputs to an AI inference system. The AI is able to discern nonlinearity between the input and output data and is able to generalize in the presence of unknown fault cases.

The harmonic study shows that the power system topology is more important than the presence of harmonics, particularly on the distant line. Since AA schemes using AI can overcome varying primary system parameters, this suggests that they will be robust in the presence of wind farm harmonics. However, on nearby lines, it would be prudent to include harmonics signatures in the calibration of AA relays. For example, in the case where neural networks are trained with fault cases [3], including harmonic emissions in training, fault data would lead to improved response in the AA relay.

VI. Conclusion and Further Work

This paper presents a modeled section of the 132 kV Scottish network, built for developing TBP and, in particular, AA. The power system model has been implemented on the RTDS, demonstrating that it is capable of stable, sustained real-time operation. Some preliminary results are presented, investigating the penetration of harmonics onto the local grid. The results suggest that in the worst case scenario, in this system, harmonics are only significant on adjacent lines. The study suggests primary system parameters, such as real power flow and the local level of generation, are more significant in determining the normalized frequency spectra of the current and voltage waveforms, on which AA relays would be based. Further work is required on load modeling, but this would require greater RTDS resource. Part 2 of this paper uses the DFIG model and contains more information on arc modeling as well as describing the algorithm itself.

Appendix A
Conductor Constants

<u>Lynx conductor</u>

DC resistance per subconductor.........0.156489 Ω/km;

Subconductor radius:........................0.976 cm;

Number of subconductors:...........................1;

<u>Lynx ground wire</u>

DC resistance................................0.1469 Ω/km;

Radius ....0.976 cm.

Appendix B
Tower Configurations

All measurements are in meters. The horizontal displacement of the second circuit is assumed to be symmetrical about the vertical axis of the tower.

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Simon P. Le Blond (M'09) received the B.Sc. (Hons.) degree in physics from the University of Southampton, Southampton, U.K., in 2004, and the Ph.D. degree in electrical and electronic engineering from the University of Bath, Bath, U.K.

His main research interests are real-time power system simulation, power system transients, as well as power system protection and AI techniques applied to power systems. He begins his engineering career with TRL of Toshiba Research Europe Ltd.

Raj K. Aggarwal (SM'91) received the B.Eng. and Ph.D. degrees in electronics and electrical engineering and the D.Eng. degree for his original and outstanding contribution to electrical power systems from the University of Liverpool, Liverpool, U.K., in 1970, 1973, and 2005, respectively.

He then joined the University of Bath, Bath, U.K., where he is currently Professor of Electrical Engineering and Head of the Electrical Power and Energy Systems Group, Department of Electronic and Electrical Engineering.

Dr. Aggarwal is/has been on several Institute of Engineering and Technology and CIGRÉ committees and has been a member of the EPSRC Scientific Advisory committee on energy. He has published many technical papers and is the recipient of several Institute of Engineering and Technology premium awards for papers published.